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Control Interaction Mitigation for the Unified Power Flow Controller

L. Dong and M. L. Crow, *Member, IEEE*

Abstract—This paper establishes that dynamic interactions can occur between multiple UPFCs installed in power systems. The existence of the dynamic interactions can adversely affect the overall system performance and lead to system instability. This paper identifies two types of interactions among FACTS controllers: low frequency inter-area interaction and high frequency controller interactions. Several control approaches are proposed to mitigate these interactions. The IEEE New England 10-machine 39-bus system is used to demonstrate the existence of the control interactions and illustrate the effectiveness of the proposed interaction mitigation controls.

Index Terms—FACTS, Fuzzy logic, Inter-area oscillations

I. INTRODUCTION

IN the US, over 150,000 miles of interconnected high-voltage transmission lines currently link generators to load centers. Under normal operation, this web of interconnecting transmission lines makes the grid highly robust and reliable. However, during stressed conditions, a failure in one location can quickly propagate across the grid in a complex and dramatic way, potentially leading to widespread blackouts. Less severe, but equally costly, is the increasing challenge of mitigating transmission congestion. Transmission congestion has been estimated to cost consumers hundreds of millions of dollars annually. Although transmission congestion can be greatly alleviated by adding new transmission lines, investment in new transmission facilities lags considerably behind investment in new generation and growth in electricity demand. Construction of high-voltage transmission facilities is expected to increase by only 6 percent during the next decade, whereas electricity demand and new generation capacity are each projected to increase by almost 20 percent during the next decade. This lag in transmission growth is due mainly to public opposition that ranges from esthetic to environmental reasons.

In a traditional vertically integrated utility structure, the scheduling of generators was the primary means for adjusting power flow through the network. However, as the vertically integrated utility structure is replaced by open access, this

means of transmission power flow control has been diminished. Thus new controllers must be developed that will allow transmission providers direct control of the grid. Introducing advanced transmission technologies such as flexible AC transmission systems (FACTS) will help reduce transmission congestion and more fully utilize the existing transmission system. The transmission systems of tomorrow must incorporate advanced hardware and software technologies to increase safe utilization of existing facilities to increase reliable long distance power transfer. Encouraging the use of FACTS technologies is essential to make better use of existing transmission facilities and reduce the number of new facilities that are needed, but their utilization brings new problems as well.

In large interconnected networks, the placement of more than one FACTS device in the same region or electrical area will be a natural consequence of the growing use of this technology. However, adverse interactions may occur between different FACTS devices if their controls are not coordinated. The existence of dynamic interactions among FACTS controls can adversely affect the overall performance and even lead to dynamic instability of the system. Adverse interactions among FACTS controls must be identified and alleviated before multiple FACTS devices can be safely deployed in a system. Recently, a number of studies have addressed the control interaction behavior between FACTS devices [1]-[3]. In [1], Pilotto et al. have presented the possible control interactions among FACTS device (SVC and TCSC) operating in the same electrical area. By applying a coordinated controller design based on a trial-and-error approach for both the TCSC and SVC, the undesirable control interaction problem is solved. A Linear Matrix Inequalities (LMI) technique has been used by Mekki et al. [2] to reduce control interactions between FACTS devices and Power System Stabilizers (PSS) based on a 4-machine test system. Ammari et al. [3] have also used LMI technique to solve for the interactions between dynamic loads and FACTS controllers.

This paper extends these previous works by focusing on the investigation and mitigation of the potential dynamic control interactions between UPFC controllers installed in multimachine systems. Two different interaction phenomena are identified by their distinctive frequency characteristics: low frequency modal interaction and high frequency interaction. Due to the difference of the interaction phenomena, two approaches are proposed respectively to

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eliminate these adverse interactions.

II. THE UNIFIED POWER FLOW CONTROLLER MODEL

The unified power flow controller, or UPFC, is the most versatile FACTS device. It consists of a combination of a shunt and series branches (STATCOM and SSSC) connected through the DC capacitor. The series connected inverter injects a voltage with controllable magnitude and phase angle in series with the transmission line, therefore providing real and reactive power to the transmission line. The shunt-connected inverter provides the real power drawn by the series branch and the losses, and can independently provide reactive compensation to the system. The UPFC model is given by

$$\frac{1}{\omega_s} \dot{i}_{d1} = -\frac{R_{s1}}{L_{s1}} i_{d1} + \frac{\omega}{\omega_s} i_{q1} + \frac{k_1}{L_{s1}} \cos(\alpha_1 + \theta_1) V_{dc} - \frac{1}{L_{s1}} V_1 \cos(\theta_1) \quad (1)$$

$$\frac{1}{\omega_s} \dot{i}_{q1} = -\frac{R_{s1}}{L_{s1}} i_{q1} - \frac{\omega}{\omega_s} i_{d1} + \frac{k_1}{L_{s1}} \sin(\alpha_1 + \theta_1) V_{dc} - \frac{1}{L_{s1}} V_1 \sin(\theta_1) \quad (2)$$

$$\frac{1}{\omega_s} \dot{i}_{d2} = -\frac{R_{s2}}{L_{s2}} i_{d2} + \frac{\omega}{\omega_s} i_{q2} + \frac{k_2}{L_{s2}} \cos(\alpha_2 + \theta_1) V_{dc} - \quad (3)$$

$$\frac{1}{L_{s2}} (V_2 \cos(\theta_2) - V_1 \cos(\theta_1))$$

$$\frac{1}{\omega_s} \dot{i}_{q2} = -\frac{R_{s2}}{L_{s2}} i_{q2} - \frac{\omega}{\omega_s} i_{d2} + \frac{k_2}{L_{s2}} \sin(\alpha_2 + \theta_1) V_{dc} - \quad (4)$$

$$\frac{1}{L_{s2}} (V_2 \sin(\theta_2) - V_1 \sin(\theta_1))$$

$$\frac{C}{\omega_s} \dot{V}_{dc} = -k_1 \cos(\alpha_1 + \theta_1) i_{d1} - k_1 \sin(\alpha_1 + \theta_1) i_{q1} \quad (5)$$

$$-k_2 \cos(\alpha_2 + \theta_1) i_{d2} - k_2 \sin(\alpha_2 + \theta_1) i_{q2} - \frac{V_{dc}}{R_{dc}}$$

where i_{di} and i_{qi} are the injected dq converter currents, V_{dc} is the voltage across the DC capacitor, R_{dc} represents the switching losses, R_{si} and L_{si} are the coupling transformer impedances, $V_1 \angle \theta_1$ and $V_2 \angle \theta_2$ are the terminal voltages of the UPFC. The control inputs are the shunt and series firing angles α_1 and α_2 , and modulation indices k_1 and k_2 respectively.

The power balance equations at bus 1 are given by:

$$0 = V_1 ((i_{d1} - i_{d2}) \cos \theta_1 + (i_{q1} - i_{q2}) \sin \theta_1) - \quad (6)$$

$$V_1 \sum_{j=1}^n V_j Y_{1j} \cos(\theta_1 - \theta_j - \phi_{1j})$$

$$0 = V_1 ((i_{d1} - i_{d2}) \sin \theta_1 - (i_{q1} - i_{q2}) \cos \theta_1) - \quad (7)$$

$$V_1 \sum_{j=1}^n V_j Y_{1j} \sin(\theta_1 - \theta_j - \phi_{1j})$$

and at bus 2:

$$0 = V_2 ((i_{d2}) \cos \theta_2 + (i_{q2}) \sin \theta_2) - \quad (8)$$

$$V_2 \sum_{j=1}^n V_j Y_{2j} \cos(\theta_2 - \theta_j - \phi_{2j})$$

$$0 = V_2 ((i_{d2}) \sin \theta_2 - (i_{q2}) \cos \theta_2) - \quad (9)$$

$$V_2 \sum_{j=1}^n V_j Y_{2j} \sin(\theta_2 - \theta_j - \phi_{2j})$$

The UPFC has four control objectives: the shunt bus voltage, the DC capacitor voltage, and the line active and reactive power. In the synchronously rotating dq reference frame, the injected voltage can be split into E_{1d} and E_{1q} on the shunt side, and E_{2d} and E_{2q} on the series side. By proper control of these voltages, the four control objectives can be met. One PI-based control is shown in Fig. 1.

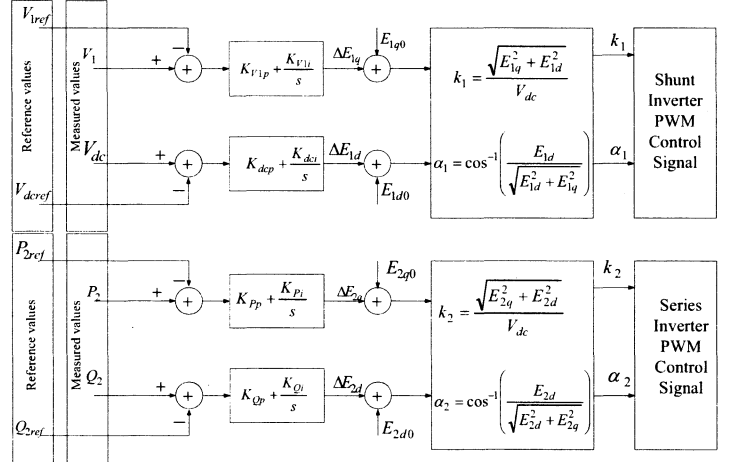


Fig. 1. UPFC Control

III. HIGH FREQUENCY INTERACTION

FACTS devices have the capability to provide fast-acting control. While providing rapid control, this may also lead to possible adverse high frequency interactions between these fast power electronic devices. The separate PI-based control design of each UPFC assumes the complete dynamic decomposition of the system. However, there exist interactive dynamics among UPFC controllers since the dynamic changing of power flow on one specific transmission line may influence the power flows on the other lines especially when FACTS devices are installed in the same area, and sometimes the same bus. Without taking account of the interactive dynamics among the controllers, unsatisfactory high frequency interactions can occur when the controllers are in joint operation. This effect can be illustrated by considering the New England system shown in Fig. 2.

Consider the example contingency in which a three-phase fault occurs on bus 39 and is cleared after 100ms by opening line 1-39. The system dynamic response to this contingency is shown in Fig. 3. Note that although large poorly damped oscillations occurs, the system remains stable.

Consider the case in which two FACTS devices, UPFC₁ and UPFC₂, are installed in this system. UPFC₁ is located at line 25-26 and controls active and reactive power on the line and maintains a constant voltage magnitude on bus 25.

UPFC₂ is

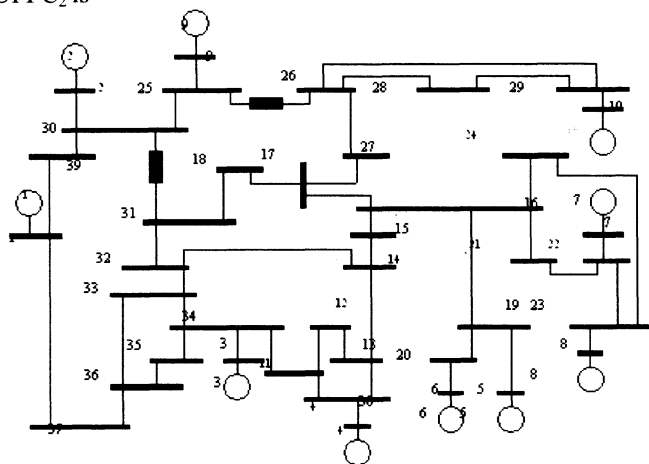
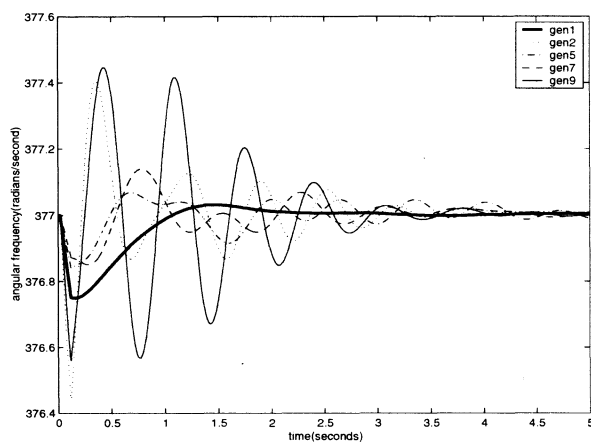
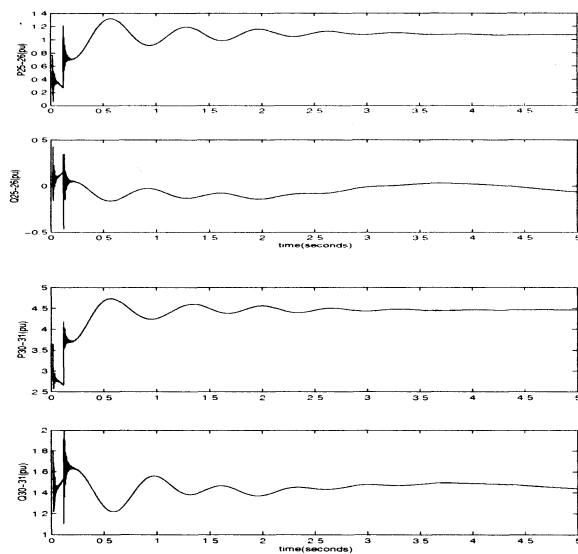


Fig. 2. IEEE 39Bus New England System



(a)

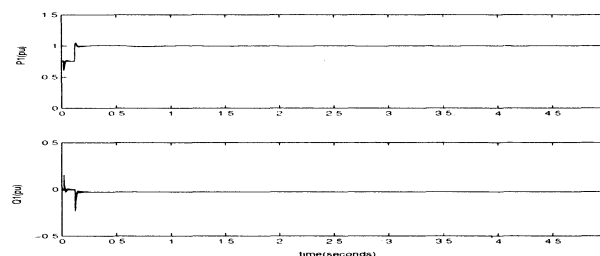


(b)

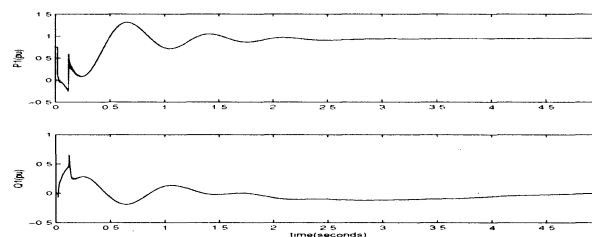
Fig. 3. No control (a) generator frequencies (b) line flows

located at line 30-31 and controls active and reactive power on the line and maintains a constant voltage magnitude on bus 30. If either of the controllers acts independently, the system stability is vastly improved as shown in Fig. 4 (a) and (b),

which show UPFC₁ acting alone and UPFC₂ acting alone respectively. From these results, it would be intuitive to believe that combining the control efforts of the two UPFCs would further improve the control responses. However, the combined response of the UPFCs is shown in Fig. 5. Note that while the system is technically stable, the interaction of the UPFCs causes an unacceptable oscillatory interaction.



(a)



(b)

Fig. 4. Line Power Flows (a) UPFC1 only (b) UPFC2 only

This leads to the basic question: what mechanism is causing this interaction? To delve into this issue, compare the magnified UPFC reactive power flows shown in Fig. 6. The reactive power flows in each UPFC are approximately 90° out of phase with each other. This indicates that the reactive power flow controls of each UPFC are “ringing” against each other. This conclusion is supported by considering the same system configuration and fault when the reactive power controls of the UPFCs are disabled. These results are shown in Fig. 7. The oscillatory interactions have disappeared, but of course, the reactive power is no longer held at the desired reference value. The problem therefore becomes one of developing a reactive power control that does not cause the

controllers to adversely interact.

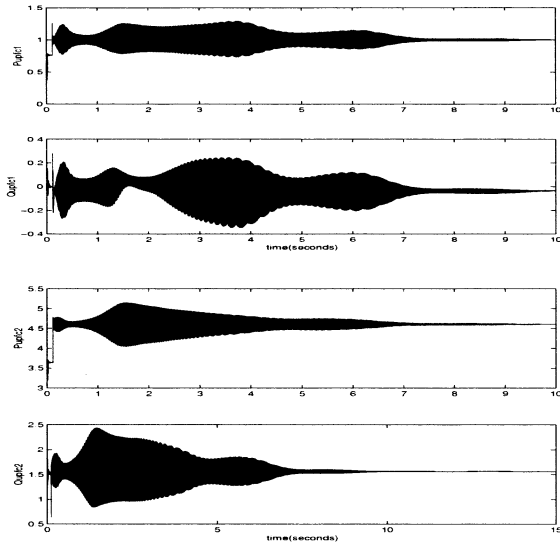


Fig. 5. Line power flows UPFC1 and UPFC2

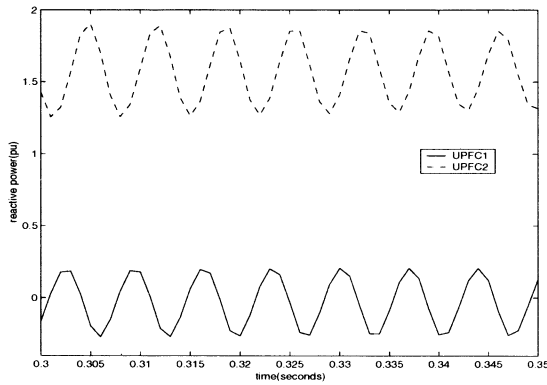


Fig. 6. Comparison of line reactive power flow

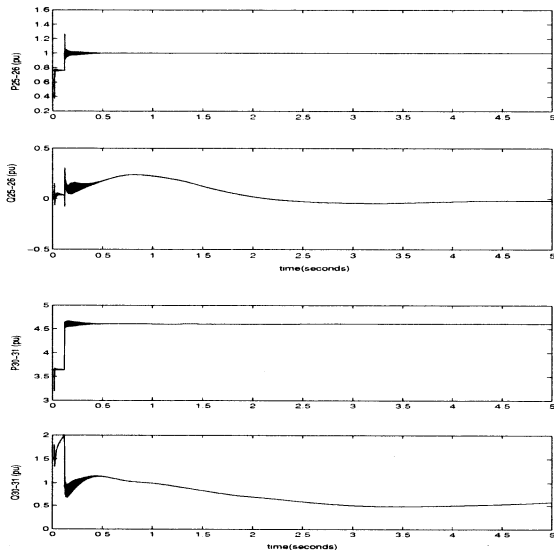


Fig. 7. Line power flow UPFC1 and UPFC2 with no reactive power control

One approach that retains the simple implementation of the UPFC PI controller shown in Fig. 1 is a fuzzy PI controller. A conventional PI controller uses an analytical expression of the

following form to compute the control action

$$u(t) = K_p \cdot e(t) + K_i \cdot \int e(t) dt \quad (10)$$

The discrete-time and incremental form is written as

$$\Delta u(k) = K_p \cdot \Delta e(k) + K_i \cdot T \cdot e(k) \quad (11)$$

where $\Delta u(k)$ is the change of control output such that $\Delta u(k) = u(k) - u(k-1)$, $e(k)$ is the error such that $e(k) = y_{sp} - y(k)$, where $y(k)$ is the system output and y_{sp} is the desired system output, $\Delta e(k)$ is change of error and $\Delta e(k) = e(k) - e(k-1)$, k is the k -th sampling time and T is the sampling time.

The PI controller has a simple control structure and is easy to design by adjusting the two controller parameters K_p and K_i to achieve acceptable performance. The main idea of the hybrid fuzzy controller is to use the fuzzy proportional (P) controller to improve the overshoot and rising time response and a conventional integral (I) controller to reduce the steady-state error [4]. Therefore, by combining the advantages of a conventional PI controller and a nonlinear fuzzy logic control technique, this controller is constructed by replacing the proportional term in the conventional PI controller with an incremental fuzzy logic controller.

In this fuzzy controller, membership functions N (negative), Z (zero), and P (positive) assigned with linguistic variables are used to fuzzify the error and its derivative. For simplicity, it is assumed that the triangular membership functions are symmetrical and each one overlaps the adjacent functions by 50%. The rules that map the fuzzy inputs to a fuzzy output are given in Table I.

Table I
Fuzzy Rules

Rules	Inputs		Output $\Delta u_f(k)$
	$e(k)$	$\dot{e}(k)$	
1	P	P	P
2	P	Z	P
3	P	N	Z
4	Z	P	P
5	Z	Z	Z
6	Z	N	N
7	N	P	Z
8	N	Z	N
9	N	N	N

The output $\Delta u_f(k)$ is defuzzified using a center of mass method:

$$\Delta u_f(k) = \frac{\sum_{j=1}^9 \mu_j \cdot c_j(k)}{\sum_{j=1}^9 \mu_j} \quad (12)$$

where $c_j(k)$ is the value of control output corresponding to

the membership value of input equal to unity and μ_j is the value of the membership function. The hybrid fuzzy logic controller is constructed by replacing the proportional terms in the conventional PI UPFC series controller by the output variables of the incremental fuzzy logic controller. The shunt PI controller is not changed. The modified fuzzy control scheme is shown in Fig. 8. This control is applied to the test system under the same contingency as before. The system results are shown in Fig. 9. Note that the high frequency oscillations are eliminated and the system quickly converges to the specified line power flows.

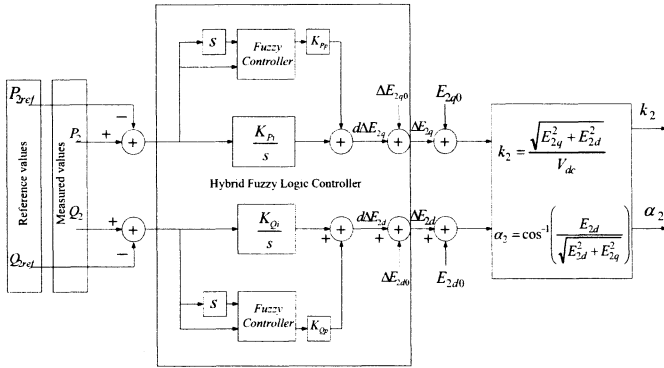


Fig. 8. UPFC hybrid fuzzy logic control

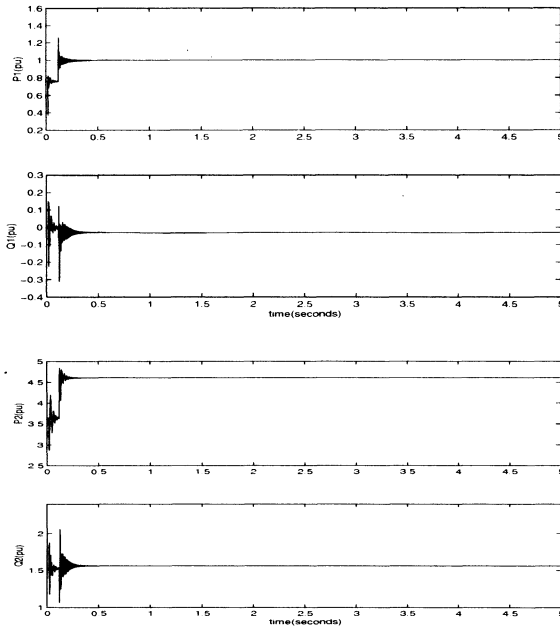


Fig. 9. Line power flows of UPFC1 and UPFC2

IV. OSCILLATORY INSTABILITY INTERACTIONS

Immediately following a system disturbance, the system generators may begin to oscillate relative to each other, causing fluctuations in system frequency, the power flows on the transmission lines and the bus voltage magnitudes. The oscillations may be local to one or more generators in an area with respect to the rest of the system (intra-area oscillation), or they may be associated with groups of generators in different

areas oscillating against each other (inter-area oscillation). Once started, they may continue to grow, causing groups of generators to lose synchronism and system oscillatory instability may occur. FACTS controllers, especially the UPFC, play a vital role in retaining power system stability under large disturbances. However, in some circumstances, interactions between the UPFC controls may actually destabilize the system, especially if more than one UPFC are installed in the same electric area, or the locations of the UPFC controllers cause part of the system to island after the clearance of a critical fault. By separating generators in one specific area from other groups of generators, the islanding group may lose synchronism with other groups and cause system instability.

The same example IEEE 39 bus New England system is used to demonstrate the existence of oscillatory instability interactions among UPFC controllers. Consider the case in which two FACTS devices, UPFC₁ and UPFC₂, are installed in lines 13-14 and line 33-32 respectively and a three-phase fault occurs on bus 37 and is cleared after 100ms duration by opening line 1-37. Both the UPFC controllers use the PI based control approach to control active and reactive power on the line and maintain a constant shunt input voltage magnitude, and each UPFC control is designed and optimized separately without considering the presence of other UPFCs. As in the previous section, if either of the controllers acts independently, the system stability is improved. However, the combined control of the two UPFCs causes system instability. The dynamic responses of the generators in Fig. 10 clearly show that the generators are pulling apart and losing synchronism. Fig. 11 shows the active and reactive power flows across the UPFCs illustrating the effect of the instability on the line flows.

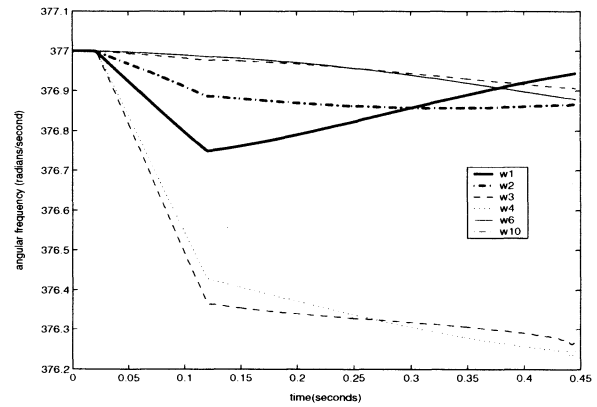


Fig. 10. Angular frequencies with PI control

Since the proposed hybrid fuzzy controller can efficiently eliminate high frequency control interaction between the UPFCs, the system dynamic responses to the same contingency are shown in Fig. 12 with the proposed hybrid fuzzy logic controller for oscillatory instability interaction. Note that while the high frequency interactions are eliminated, the system still goes to unstable; therefore a more advanced

controller is needed to eliminate the low frequency oscillatory instability caused by the UPFCs' interaction.

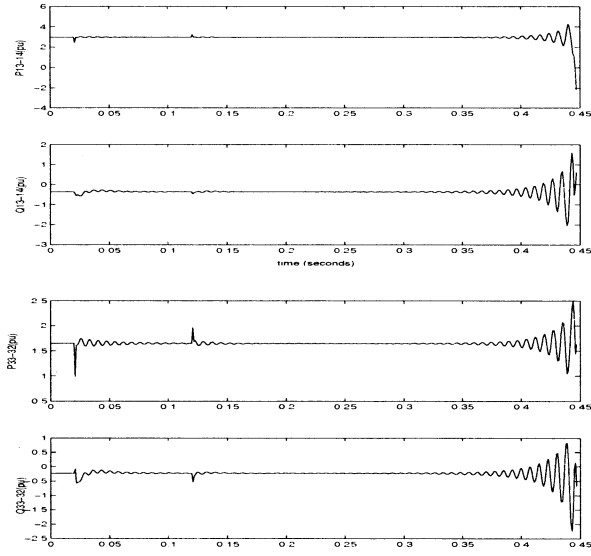


Fig. 11. UPFC line flows with PI control

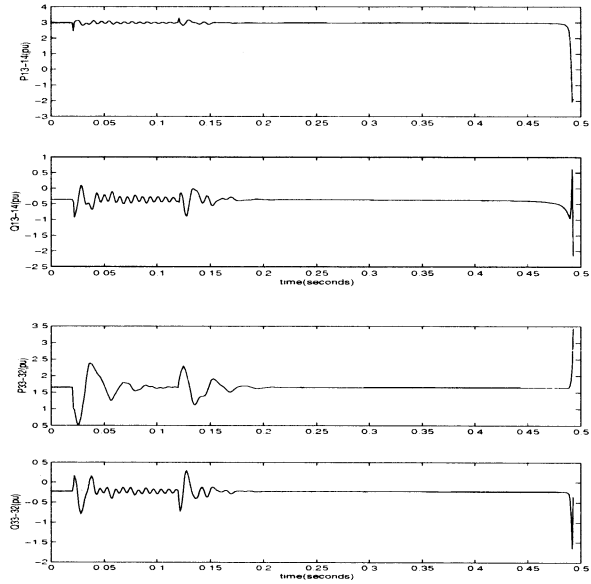


Fig. 12. UPFC line flows with fuzzy PI control

The effectiveness of the UPFCs for improving system dynamic stability is limited by using only local input signals in the controllers. The additional of selected “global” signal inputs obtained remotely from the controller make it possible to improve the controller performance. Such global inputs may be selected as frequency difference between generators, pilot bus voltages, or power flows on tie line, etc. Research in the application of phasor or wide-area-measurement-systems (WAMS) makes this approach viable. Since the instability is a low-frequency inter-area oscillation, the global inputs for the UPFCs are chosen as generator frequencies. However, due to the large size of the power system, it is not desirable to use all of the generator frequencies as additional inputs, but rather only those generators that play a significant role in the instability. These inputs are selected by calculating the

participation of each generator in the unstable mode. The additional global inputs are added to the series controller of the UPFCs such that:

$$\begin{aligned} \Delta E_{2q} &= K_{Pp} \Delta P_2 + \sum_{k=1}^n K_{\omega k Pp} (\omega_i - \omega_j) + \\ &K_{Pi} \int \Delta P_2 dt + \sum_{k=1}^n K_{\omega k Pi} \int_0^t (\omega_i - \omega_j) dt \\ \Delta E_{2d} &= K_{Qp} \Delta Q_2 + \sum_{k=1}^n K_{\omega k Qp} (\omega_i - \omega_j) + \\ &K_{Qi} \int \Delta Q_2 dt + \sum_{k=1}^n K_{\omega k Qi} \int_0^t (\omega_i - \omega_j) dt \end{aligned} \quad (13)$$

where the only non-zero coefficient $K_{\omega k Pp}$, $K_{\omega k Pi}$, $K_{\omega k Qp}$ and $K_{\omega k Qi}$ correspond to the selected generator inputs.

In the example system, generator 1, 3, 4, 6 and 10 are identified as having significant impact on the stability of the system and are incorporated into the series control of the UPFC. The effect of the “global” PI UPFC controllers is illustrated in Fig. 13 and Fig. 14. Note that the use of the global input signals enables the UPFCs to rapidly damp any line flow oscillations and the generators quickly stabilize.

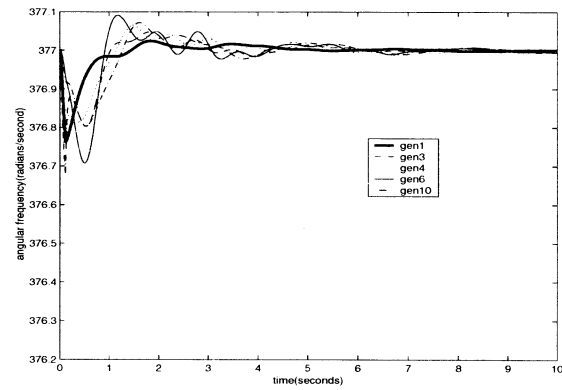


Fig. 13. Angular frequencies – PI control with global signals

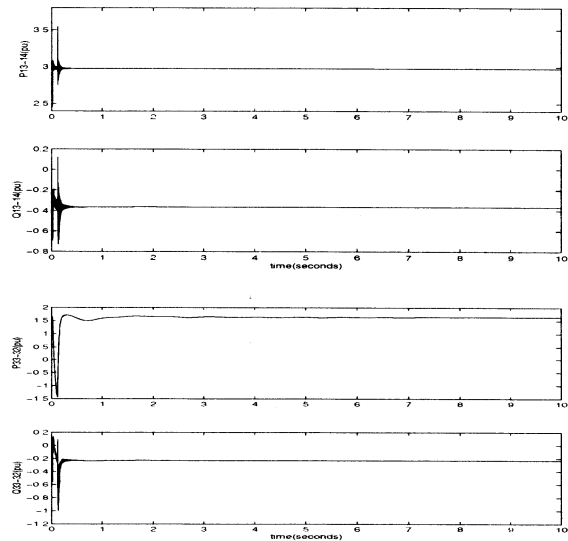


Fig. 14. UPFC line flows with PI control with global signals

V. CONCLUSION

The paper highlights two types of interactions that can occur when two or more UPFCs are placed in proximity in a power system. The first type of interaction that can occur is a high frequency interaction that may or may not destabilize the system. This interaction is the direct result of "chopping" between the series reactive power controller. A fuzzy PI control is proposed that is shown to be effective in mitigating the high frequency interactions.

A second type of interaction is a low-frequency interaction that adversely effects the inter-area oscillations of the system following a disturbance. In this case, the system can be stabilized by introducing a series of "global" signals from the dominant generators in the system into the series controller of the UPFCs.

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REFERENCES

- [1] Pilotto, L.A.S.; Long, W.F.; and Edris, A.A., "Basic Mechanisms of Control Interactions among Power Electronic-assisted Power Systems," *IEEE/PES Transmission and Distribution Conference and Exposition*, Vol. 1, pp. 397-402, 2001.
- [2] Mekki, K.; Hadjsaid, N.; Feujillet, R.; and Georges, D., "Design of Damping Controllers Using Linear Matrix Inequalities Techniques and Distant Signals to Reduce Control Interactions," *PICA 2001*, pp. 306-311, May 2001.
- [3] Ammari, S.; Besanger, Y., hadjsaid, N. and Georges, D., "Robust Solutions for the Interaction Phenomena Between Dynamic Loads and FACTS Controllers," *IEEE Power Engineering Society Summer Meeting*, Vol. 1, pp401-406, 2000.
- [4] D. Driankov, *An Introduction to Fuzzy Control*, Springer-Verlag, Berlin-Heidelberg, 1993.